

# The role of waves in magnetotail dynamics

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**Abstract.** The role of waves in the dynamics of the magnetotail has long been a topic of interest in magnetospheric physics. Although early observations of waves led to the suggestion that lower hybrid waves provided the dissipation needed for reconnection to occur, questions were raised about the amplitude of the waves and the suppression of the instability at high beta. ISEE and Geotail observations provided evidence that the waves were often large enough to enable reconnection and that large amplitude waves could occur within the current sheet. More recently, simulation studies have indicated that the Hall effect and the resulting whistler dispersion decouple the particles and that wave dissipation is not needed. However, an observational answer to the question of which small-scale structures and/or waves break the frozen in condition, decoupling of the motions of ions and electrons, during substorm reconnection is still unresolved. We briefly review previous studies of waves in the magnetotail and their association with substorms and magnetotail dynamics. The recent launch of Cluster and the precession of the Polar apogee into the equatorial plane have provided the opportunity to examine the importance of waves with more sophisticated instruments. Preliminary results of several new event studies utilizing Polar and Cluster data are presented and used to re-examine the importance of waves and nonlinear structures, such as electron holes, in substorms and magnetotail dynamics.

## I. Introduction

Scarf et al. [1974] and Gurnett et al. [1976] presented the first observations of waves in the magnetotail, which were broadband and often very intense. They also showed that the electrostatic waves, referred to as ‘broadband electrostatic noise’ or ‘BEN,’ peaked at or below the lower hybrid frequency. The observations were interpreted by Huba et al. [1977; 1981] to indicate that the plasma sheet was unstable to lower hybrid drift waves and that these waves could provide the resistivity necessary for reconnection. Concerns were raised [Coroniti, 1985; Dum, 1995] because the instability was suppressed in high beta plasmas, i.e. at the neutral

sheet, and because waves with large enough amplitudes had not been observed. Cattell et al. [1986b] suggested that the broadband waves were due to a superposition of wave modes, including an ensemble of nonlinear waves. Matsumoto et al. [1994] showed that BEN in the plasma sheet was due to an ensemble of solitary waves, bipolar nonlinear spikes in the parallel electric field. Subsequently, solitary waves have been observed throughout the magnetosphere [Ergun et al, 1998; Franz et al., 1998; Tsurutani et al., 1998; Bale et al., 1998; Cattell et al., 1999; Mangeney et al., 1999], and identified as the signature of electron holes [Matsumoto et al., 1999; Muschietti et al., 1999; Goldman et al., 1999].

ISEE-1 quasi-static electric field measurements identified a class of events consistent with the hypothesis that a ‘near-earth neutral line’ formed earthward of the satellite and subsequently propagated past it [Cattell and Mozer, 1984; Cattell et al., 1986a]. Statistical results [Cattell and Mozer, 1984] showed that the substorm-associated neutral line usually formed tailward of  $\sim 20R_E$  (this result was confirmed and expanded on by Nagai et al., 1998 and Machida et al., 1999, utilizing Geotail data). For one of the identified events, the ISEE-1 double probe electric field instrument obtained waveform captures (one every 128s) as the satellite encountered various regions in the plasma sheet and the plasma sheet boundary before, during and after the passage of the neutral line. Intense waves peaked at  $f \sim 0.5 - 0.8 f_{lh}$  and  $k\rho_e < 1$ , where  $f_{lh}$  is the lower hybrid frequency and  $\rho_e$  is the electron gyroradius, consistent with lower hybrid drift waves, were observed throughout the period of the fast flows associated with the formation and motion of the neutral line. The waves were observed at locations throughout the north-south extent of the plasma sheet, including right at the neutral sheet [Cattell and Mozer, 1986; 1987], and it was suggested that the waves were not suppressed because there were large gradients on small-scales to drive the waves and large  $B_z$ . The resistivity calculated using the observed wave amplitudes and the quasi-linear formula of Gary [1980] was large enough to enable reconnection. Cattell [1996] calculated the range of values for the Lundquist number based on ISEE and Geotail observations, for comparison to the parameter in MHD simulations.

The exciting results obtained by AMPTE/CCE in the inner magnetosphere refocused attention on the importance of that region for understanding substorm onset (see Proceedings of ICS1). This led to the development of the current sheet disruption model [Lui, 1996 and references therein], which predicts that intense waves driven by cross-field current instability (CCI) will occur at the time of onset in the region where the cross-tail current is disrupted and diverted to the ionosphere. The frequency of CCI is expected to be from about  $10^{-3}$  to  $10^{-1}$  times the lower hybrid frequency, and the waves are whistler mode [Lui, 1996]. The consistency of wave observations with this model has been addressed by a number of

authors. Sigsbee et al. [2001, 2002] have examined the relationship between fast flows and waves at frequencies ranging from the lower hybrid frequency to  $Pi2$ ’s, for a case in the mid-tail and several in the near-tail. For the fast flow event studied by Fairfield et al. [1999], Sigsbee et al. [2002] found that,  $\sim 5$  minutes after onset a burst of power extending from  $\sim 0.6 - 1$  Hz was observed, primarily in the duskward electric field. This is in the band where the CCI is predicted to occur [Lui, 1996]. In addition, a magnetic field compression at  $Pi2$  frequencies was clearly. Similar observations from GOES have been presented by Holter et al. [1994].

Recently, a number of simulations (MHD, hybrid, and full particle) of reconnection have been performed that suggest that it is the inclusion of Hall effect that is important to obtaining fast reconnection and that the specific dissipation mechanism is not important [see discussion in Birn et al., 2001, and references therein]. Wind observations [Oeris et al., 2001] have confirmed the presence of the expected Hall signature in the magnetic field in association with a substorm near-earth neutral line event. These theoretical and experimental results suggest that waves may not be required to decouple the ions; however, the question of what mechanism provides dissipation in the electron diffusion region is still open.

The above very brief review has indicated the possible importance of waves in substorm dynamics. In this paper, we describe several new studies that address this issue. Data for the Polar studies were obtained from the flux-gate magnetometer [Russell et al., 1985] and the Polar EFI [Harvey et al., 1985]. Spacecraft potential measurements, indicative of plasma density [Pedersen, 1995], and waveform captures of the 3d electric field are shown. The Cluster EFW [Gustafsson et al., 1988] provided the data for the studies in the plasma sheet near  $18R_E$ . The spacecraft potential, the quasi-static electric field and the high-time resolution electric field (9 kHz Nyquist frequency) obtained in waveform captures (called ‘bursts’) were utilized. The duration of the waveform captures varies, but is usually 10s of seconds. In section II, we discuss the implications for magnetotail reconnection of a

recently published study of solitary waves (electron holes) at the magnetopause current layer and 3d particle simulations of reconnection. Section III presents preliminary results of Cluster studies of waves in the plasma sheet at  $\sim 18 R_e$ . Observations of obtained by the Polar EFI in the inner equatorial plasma sheet during the period of August 15, 2001 to November 15, 2001, are presented in Section IV. Discussion of the results and their significance for magnetotail dynamics are briefly described in Section V.

## II. Magnetopause results: Implications for substorms and the magnetotail

Recent observations from the Polar satellite and new 3d particle simulation results have provided evidence suggesting that electron holes may play an important role in the dynamics of reconnection. Cattell et al. [2002] showed that solitary waves (electron holes) are commonly observed in and near the magnetopause current layer during subsolar, equatorial crossings of the magnetopause. In a survey of magnetopause crossings observed during March and April, 2001, solitary waves were observed in nine of the ten crossings which had associated waveform captures. The solitary waves had amplitudes up to 25 mV/m, velocities from  $\sim 150$  km/s to  $>2000$  km/s, and scale sizes the order of a kilometer (comparable to the Debye length). Almost all the observed solitary waves were positive potential structures with potentials of  $\sim 0.1$  to 5 Volts. Positive potential solitary waves moving with velocities of 1000's of km/s are consistent with electron phase-space holes, which propagate at speeds comparable to the electron thermal speed.

Drake et al. [2001] have shown that electron holes develop in 3d particle simulations of reconnection, which include a guide magnetic field. The electron holes strongly scatter the electrons, and produce anomalous resistivity. The experimental and theoretical results provide strong support for the idea that electron holes play a critical role in the reconnection process at the Earth's magnetopause [Drake et al., 2002] and may, therefore, be important in other regions where reconnection occurs. Additional studies are underway to verify this idea.

## III. Cluster observations of solitary waves and large amplitude waves in the plasma sheet

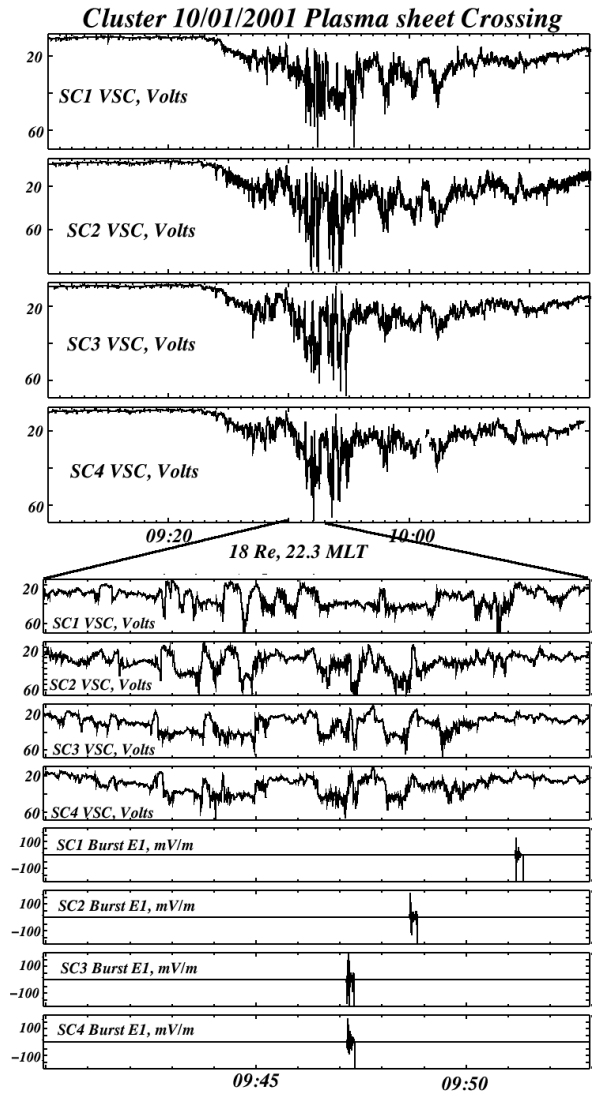


Figure 1. Overview of Cluster spacecraft potential and burst electric field on 10/1/2002.

Cluster EFW data have been used to study waves in the tail near  $18 R_e$ . Plasma sheet boundary crossings, as observed in the spacecraft potential by the four satellites, were cross-correlated to determine the propagation speed and orientation of the boundaries. The quasi-static electric field was used to calculate the  $\mathbf{E} \times \mathbf{B}$  velocity of the plasma. Because the Cluster EFW only measures the two components of the electric field in the satellite spin plane, the assumption that  $\mathbf{E} \cdot \mathbf{B} = 0$  is utilized to calculate the third component. Note that this is a reasonable assumption on these large

scales and has been used in many studies of ISEE data (see Cattell and Mozer, 1984). The wave characteristics were determined from the waveform capture data. Note that single probe voltage measurements, needed to obtain timing information on the solitary waves, are only available for recent events. Analysis of speed of solitary waves using single probe voltages is in progress and will not be discussed in this paper.

The top half of Figure 1 presents an overview of the spacecraft potential measured by the four Cluster satellites, for 1 1/2 hours, as they traversed the plasma sheet, plasma sheet boundary and lobe at  $\sim 18$  Re and 22.3 MLT. The spacecraft potential is plotted so that it increases downward, and the density increases upward. An approximate density scale based on Pedersen [1995] is shown on the right. SC3 and SC4 were separated by  $\sim 2000$  km in the  $X_{GSE}$  direction and had only a  $\sim 140$  km separation in  $Y_{GSE}$ . SC4 was the most tailward of the four satellites. SC2 was  $\sim 800$  km duskward and SC1 was  $\sim 1000$  km downward. The large-scale features of the density observed by all four satellites are very similar. Cross-correlation of the potential shows that the boundary crossing from plasma sheet to lobe at  $\sim 9:46$  (just prior to the waveform captures at SC3 and SC4) was propagating at  $\sim 400$  km/s in the (0.2, 0.8, 0.4) GSE direction. Subsequent crossings were similar, consistent with the observed encounters being due to a surface wave propagating primarily in the Y-direction along the boundary. Variable  $\mathbf{ExB}$  flows up to  $\sim 1000$  km/s were observed during this interval.

The bottom half of Figure 1 shows an expanded view of thirteen minutes, covering the period when the waveform captures were acquired. The top four panels plot the spacecraft potential from SC1 through SC4, and the next four panels plot one component of the electric field measured in the waveform capture. The density structure observed by SC3 and SC4 was very similar on these scales (consistent with the observed propagation being primarily in the  $Y_{GSE}$  direction). Both satellites also acquired waveform captures at the same time (note that the burst mode was such that each satellite kept the interval with the largest waves). All four satellites observed intense low frequency waves (up to 400

mV/m peak-to-peak) with peak frequencies varying from the ion cyclotron frequency to the lower hybrid frequency and higher.

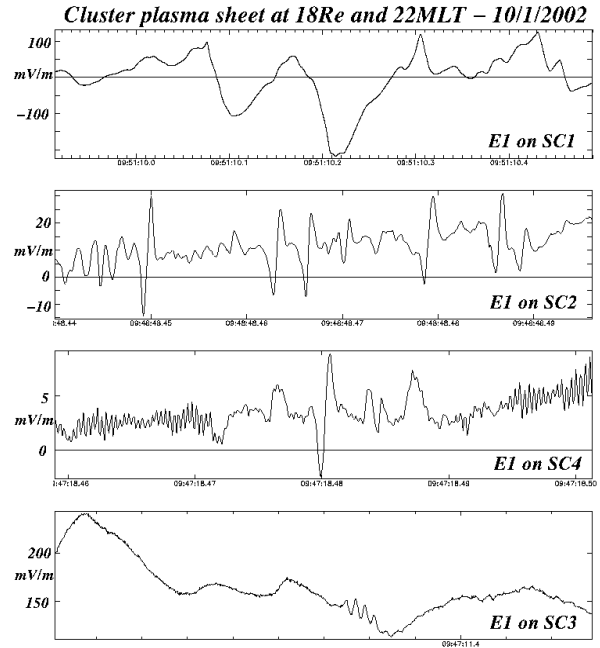


Figure 2. A snapshot from within the burst on each Cluster spacecraft (times and time intervals are different). Tic marks correspond to 0.01s.

Figure 2 shows a short interval from the burst on each satellite. The intervals are at different times and have different time scales. In each plot, the tic marks correspond to 0.01s. Large amplitude low frequency waves ( $\sim f_{lh}$ ) are seen by SC1 and SC3. Solitary waves are seen by SC2 and SC4. At SC2, the solitary waves are associated with more sinusoidal waves forms at comparable frequencies, whereas much higher frequency waves were observed in association with the solitary waves at SC4. At both satellites, the solitary waves were observed as the satellite exited the plasma sheet in a region with a large density gradient.

In a study of Cluster plasma sheet events, a large variety of plasma waves were observed in association with fast  $\mathbf{ExB}$  flows and/or with plasma sheet boundary crossings, as was earlier observed on ISEE and AMPTE. Large amplitude ( $>100$  mV/m) waves near the lower hybrid frequency (consistent with lower hybrid drift waves) are commonly seen. The largest

amplitudes observed were at the outer edge of the plasma sheet boundary (in a lobe to plasma sheet transition) on the 10/1/2001 event shown above. Solitary waves with durations of  $\sim 0.5$ -5 ms and amplitudes up to  $>100$  mV/m are also frequently seen. Solitary waves are not always seen by all four satellites. The association of solitary waves with other wave modes is quite variable. Sinusoidal waves from  $\sim 600$  Hz to 800 Hz are sometimes seen in association with the solitary waves.

Timing of the motion of the plasma sheet boundary has been performed for crossings occurring near Cluster apogee on four different days. The most accurate timings are usually obtained from crossings from the plasma sheet to the lobe ('plasma sheet thinnings'). Velocities range from  $\sim 50$  km/s to a high of  $\sim 500$  km/s, with most values in the range of 100 to 150 km/s. The propagation direction varies from primarily along the  $Z_{GSE}$  to primarily along the  $Y_{GSE}$ .

#### IV. Observations in the inner plasma sheet

The Polar satellite has had many interesting encounters with the equatorial inner plasma sheet. Figure 3 plots a plasma sheet boundary crossing at 8.5 Re,  $L=10$  and 22:45 MLT during the 10/22/2002 magnetic storm. The crossing can be seen in the spacecraft potential (first panel) and in  $B_x$  (second panel). The waves observed in the magnetic field (and dc electric field, not shown) have been identified as Alfvén waves with smaller-scale kinetic Alfvén waves superimposed on them [Wygant, 2002]. The duration of the burst can be seen in the fifth panel,  $Ex_{fac}$ . The burst occurred within the region of the largest field-aligned current associated with the Alfvén waves (see third panel.  $By$ ). Examples of solitary waves are shown in the sixth panel, a 0.08s snapshot of the parallel electric field from within the burst. This snapshot shows a train of solitary waves with peak-to-peak amplitudes up to 70 mV/m and positive potentials, consistent with electron holes.

All the Polar high time resolution waveform captures from 8/15-11/15/2001 (tail season) have been examined for solitary waves, utilizing an automatic program (see Dombeck et al., 2001 for

details on this program). Solitary waves are commonly observed. Velocities range from  $\sim 300$  km/s  $\rightarrow$   $>2500$  km/s, and scale sizes from  $\sim 1$ -15 km. Potentials are a few to  $\sim 200$  V. There are cases with net potentials of  $\sim 1$  to 40 V. Almost all the events are positive potential, fast-moving bipolar pulses, consistent with electron holes, as seen elsewhere in the outer magnetosphere.

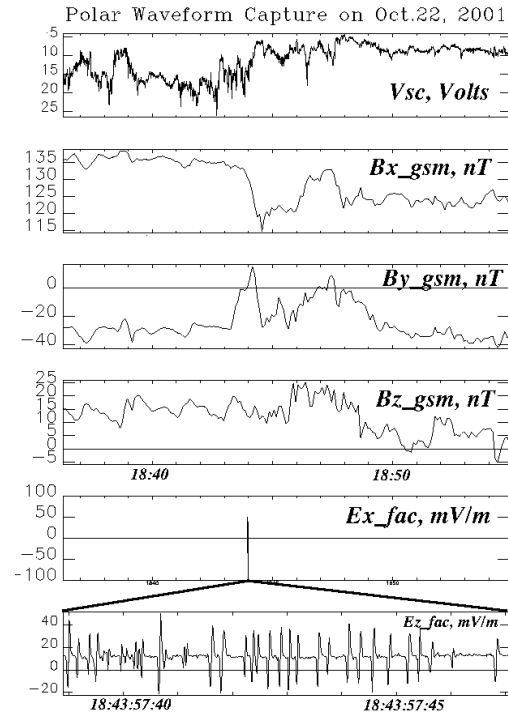


Figure 3. Storm-time crossing of plasma sheet boundary by Polar. Top four panels show the large-scale structure on the spacecraft potential (density) and magnetic field. Bottom two panels show the electric field waveform capture.

#### V. Summary and Conclusions

ISEE and Geotail studies showed that waves near the lower hybrid frequency can occur throughout the plasma sheet during active times and can provide the resistivity for reconnection to occur. These studies were limited because they used single-point measurements with only short intervals of waveform captures and due to the low bit rates and/or saturation amplitudes of the waveform captures. Cluster has shown that lower hybrid waves (up to  $>200$  mV/m), large amplitude waves at higher frequencies and solitary waves

(20->100 mV/m) occur within the plasma sheet and plasma sheet boundary. Cluster is beginning to provide information on the scale sizes of the region over which the waves occur, as well as their association with the size of gradients and with fast  $\mathbf{E} \times \mathbf{B}$  flows. Comparison with Polar magnetopause observations and 3d simulations of reconnection suggest that solitary waves may provide critical dissipation in the electron diffusion region during magnetotail reconnection.

Polar data show that large amplitude waves near the lower hybrid frequency and large amplitude solitary waves (20-100 mV/m) also commonly occur within the inner equatorial plasma sheet and plasma sheet boundary. Preliminary analysis of several storm events provides evidence that cross-scale coupling may be important since Alfvén waves, kinetic Alfvén waves, lower hybrid waves and solitary waves are often seen together. In the inner equatorial plasma sheet, Polar has observed large solitary waves in association with magnetic dipolarizations within geomagnetic storms. The role of these small-scale structures and the large amplitude waves in both substorm and storm dynamics is under investigation.

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